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REPORT DOCUMENTATION PAGE

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1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release, distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 87-0671
6a. NAME OF PERFORMING ORGANIZATION THE UNIVERSITY OF TEXAS AT AUSTIN; 6b. OFFICE SYMBOL (If applicable) AF 4	7a. NAME OF MONITORING ORGANIZATION AFOSR
6c. ADDRESS (City, State and ZIP Code) DEPARTMENT OF CIVIL ENGINEERING ECJ 5.2 AUSTIN, TX 78712	7b. ADDRESS (City, State and ZIP Code) AFOSR/NA Bolling AFB, DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AF OFFICE OF SCIENTIFIC RESEARCH; 8b. OFFICE SYMBOL (If applicable) AFOSR/NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-81-0202
8c. ADDRESS (City, State and ZIP Code) BOLLING AFB DC 20332-6448	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO. 61120F; PROJECT NO. 2302; TASK NO. C2; WORK UNIT NO.
11. TITLE (Include Security Classification) BEHAVIOR OF HIGH STRENGTH CONCERET UNDER BIAXIAL LOADING	
12. PERSONAL AUTHOR(S) DAVID W FOWLER, E NELSON, R CARRASQUILLO	
13a. TYPE OF REPORT FINAL; 13b. TIME COVERED FROM 1 Jun 84 TO ~~15 Dec 85~~ 14 Jul 85	14. DATE OF REPORT (Yr., Mo., Day) JULY 1986; 15. PAGE COUNT 8
16. SUPPLEMENTARY NOTATION	
17. COSATI CODES: FIELD / GROUP / SUB. GR.	18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) HIGH-STRENGTH CONCRETE, FATIGUE, BIAXIAL TESTING, PLAIN CONCRETE, CYCLIC TESTING

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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Research at The University of Texas has been conducted to determine the properties and behavior of plain, high-strength concrete subjected to biaxial-cyclic compression. Static and dynamic tests were performed on a total of 95 specimens which consisted of 5-in. square x 1/2-in. thick plates of concrete. Tests were performed in a biaxial test machine developed at The University of Texas. The primary variables studies were the maximum stress level, expressed as a percent of the uniaxial-static compressive strength, and the biaxial stress ratio, expressed as the ratio of the

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL DR SPENCER T WU	22b. TELEPHONE NUMBER (Include Area Code) 202- 767-4935	22c. OFFICE SYMBOL AFOSR/NA

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE. UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

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vertical to horizontal stress. Other variables included the stress range and the effect of the moisture content in the material.

Results indicated that for specimens tested in fatigue at maximum stress levels below approximately 76 percent, failure occurred at a higher number of load cycles as the biaxial stress ratio decreased. Endurance limits for a fatigue life of two million cycles were found in the range of 47 to 52 percent of the uniaxial-static compressive strength. The effect of cycling below the fatigue limit resulted in post-fatigue specimens having an increase in uniaxial-static strength over the control specimens of about 39 percent.

A least squares analysis was performed on the data for prediction of the fatigue strength of high-strength concrete subjected to biaxial-cyclic compression. Second order polynomials were selected to predict the fatigue strength as a function of the number of cycles to failure. The equations for the prediction of the fatigue strength are presented in the form of a failure envelope which illustrates the fatigue strength of high-strength concretes as a function of the stress ratio and the number of cycles to failure. Equations are also given for the fatigue strength with a 90 percent confidence level, and for a life of two million cycles, yield maximum stress levels of 52.4, 51.3, 48.7, and 47.2 percent at stress ratios of 0.0. 0.2, 0.5, and 1.0 respectively.

AFOSR-TR- 87-0671

FINAL TECHNICAL REPORT

BEHAVIOR OF HIGH-STRENGTH CONCRETE UNDER BIAXIAL LOADING

for the period

June 1, 1984 to July 14, 1985

Submitted by

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to

United State Air Force

Office of Scientific Research

Bolling Air Force Base

Grant No. AFOSR-81-0202

Department of Civil Engineering

The University of Texas at Austin

Summary

Experimental studies have been conducted on high-strength concrete to study its fatigue behavior under biaxial-cyclic loading. Thin square plate specimens were tested at maximum stress levels which approximated varying percentages of their uniaxial-static strength. For each maximum stress level, four principal stress ratios were tested. The test program included statically-tested control specimens and cyclically-tested fatigue specimens for a total of ninety-five experiments. The program concentrated on a biaxial state of stress with compression applied in both directions. The experimental program for investigating the compression-tension and tension - tension states of stress was initiated for both static and cyclic loads.

The results included uniaxial-static strength of the control specimens, the fatigue strength of the cyclic specimens, and the post-fatigue strength of the "run out" specimens. The static strength of the control specimens was lower than the cylinder strength due to less confinement in the biaxial testing machine. For the cyclic tests, three replications of each combination of maximum stress level and principal stress ratio were performed. Observing behavior based on the principal stress ratio, the higher stress ratios produced no enhancement in the fatigue strength when the maximum stress level was reduced below a certain level. Consequently, the endurance limits were lower for the two higher stress ratios. The specimens which were cycled at maximum stress levels that did not cause failure, or "run-out" specimens, were used to observe the endurance limit and were retested statically. The effect of cycling below that limit was found beneficial to the uniaxial static strength of these specimens.

The prediction of the fatigue strength for a given number of cycles was facilitated with the application of a least-squares polynomial regression to the data points. A second order polynomial function was found for each stress ratio which minimized the standard deviation to the data. The least-squares functions show stress ratios other

than the uniaxial case predominating until approximately 300 cycles. After that region, the lower stress ratios showed greater fatigue strength for a given number of cycles.

Objectives

The objectives of this area of the research program are as follows:

1. Determination of the behavior of high-strength concrete under cyclic landing and establish fatigue properties for the material.
2. To study the significance of a biaxial state of stress upon the fatigue behavior, to indicate if there is enhancement of the fatigue strength for higher stress ratios.
3. Determine an approximate fatigue limit for the material by cycling at sequentially lower maximum stress levels until a limit is found at which specimens do not fail.
4. Determine the effect of cycling below that endurance limit by studying the behavior of post-fatigue specimens.
5. Establish criteria for prediction of the fatigue strength. For design purposes, employ confidence intervals to allow for scatter of experimental data.

Status of Research

Research at the University of Texas has been conducted to determine the properties of plain, high-strength concrete subjected to a biaxial state of stress. One phase was to investigate its fatigue behavior under compression - which includes the determination of the above objectives. The investigation constitutes part of a larger test program where studies were made into the static and cyclic behavior of the material in all phases of biaxial stress, i.e., compression - compression, compression-tension, and tension-tension. The completed phase concentrates on the biaxial compression state of stress.

Tension load plattens have been built and successfully tested. An epoxy adhesive has been identified for bonding the load plattens to the specimens without the confining effects inherent in the use of friction - type plattens.

Based on the current experimental results, the following conclusions for the fatigue bnehavior of high-strength concrete under biaxial-cyclic compression can be summarized.

1. The biaxial state of stress does not enhance the fatigue strength of HSC below maximum stress levels of approximately 76 percent; in fact, stress ratios other than 0.0 cause a detrimental effect on the fatigue strength below this level.
2. For stress ratios of 0.0 and 0.2, the fatigue limit was near 50 percent. For stress ratios of 0.5 and 1.0, the fatigue limit was near 45 percent. These fatigue limits were found for a life of two million cycles.

Figure 1 shows maximum stress levels, S_m, versus number of cycles for all stress ratios, SR. Figure 2 shows the relationships based on least squares for all four stress ratios.

Conclusions can also be made regarding the static testing of the control and post-fatigue specimens:

1. The ratio of the compressive strength of the control specimens to that of the cylinder strength was 62 percent.
2. The effect of cycling below the fatigue limit was beneficial to the uniaxial-static strength of the specimens. The post-fatigue specimens indicated an increase in strength over the control specimens of 37 percent. Isolating the values of compressive strength for those which had been cycled at stress ratios of 0.5 and 1.0, the increase in compressive strength was 44 and 48 percent, respectively.
3. The effect of cycling also produced more consistency and linearity in the stress-strain behavior of the post-fatigue specimens. Failure modes from these specimens also exhibited more consistency in the type of failure.

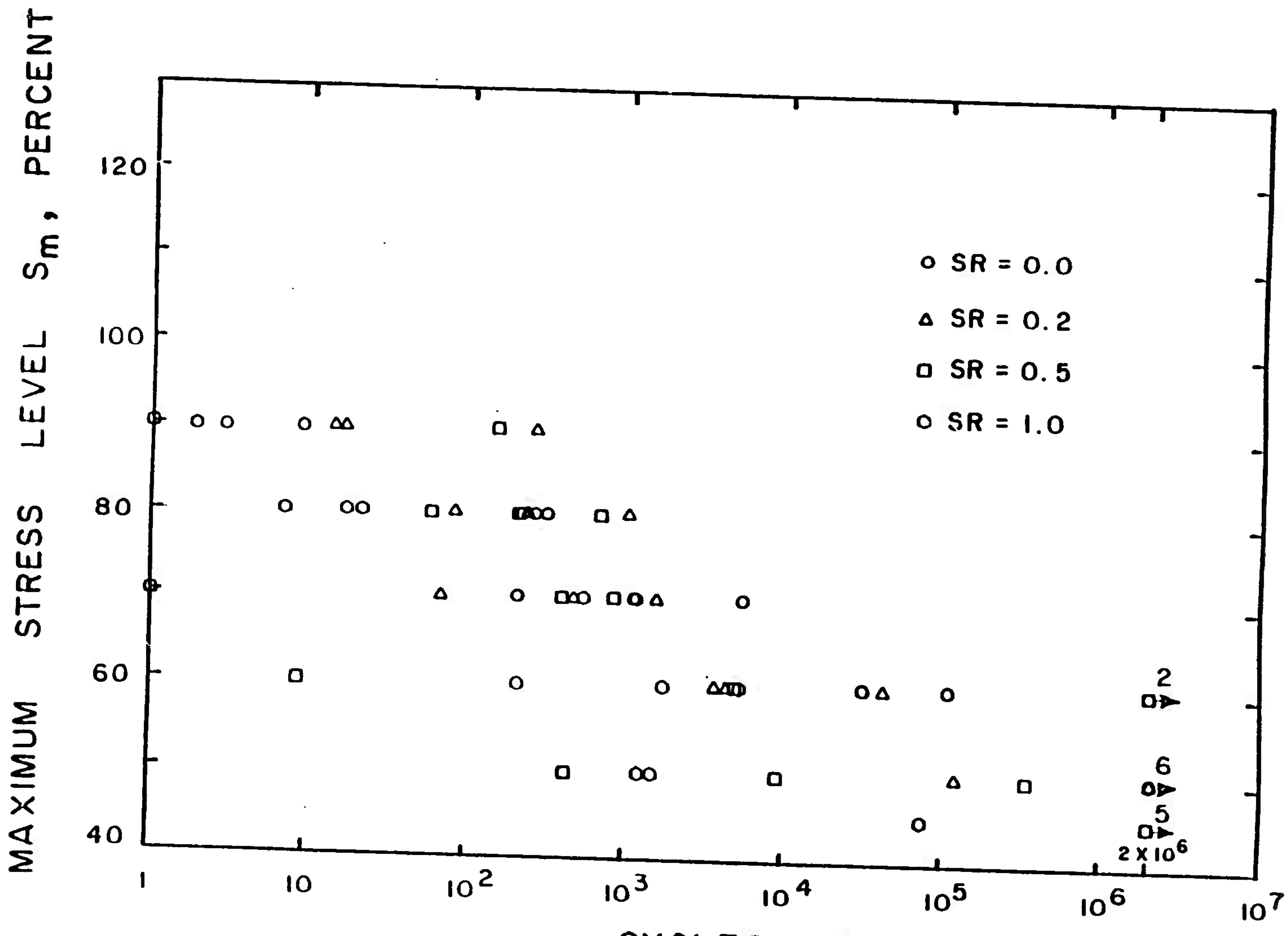

Fig. 1 S_m-N Relationship for all Stress Ratios.

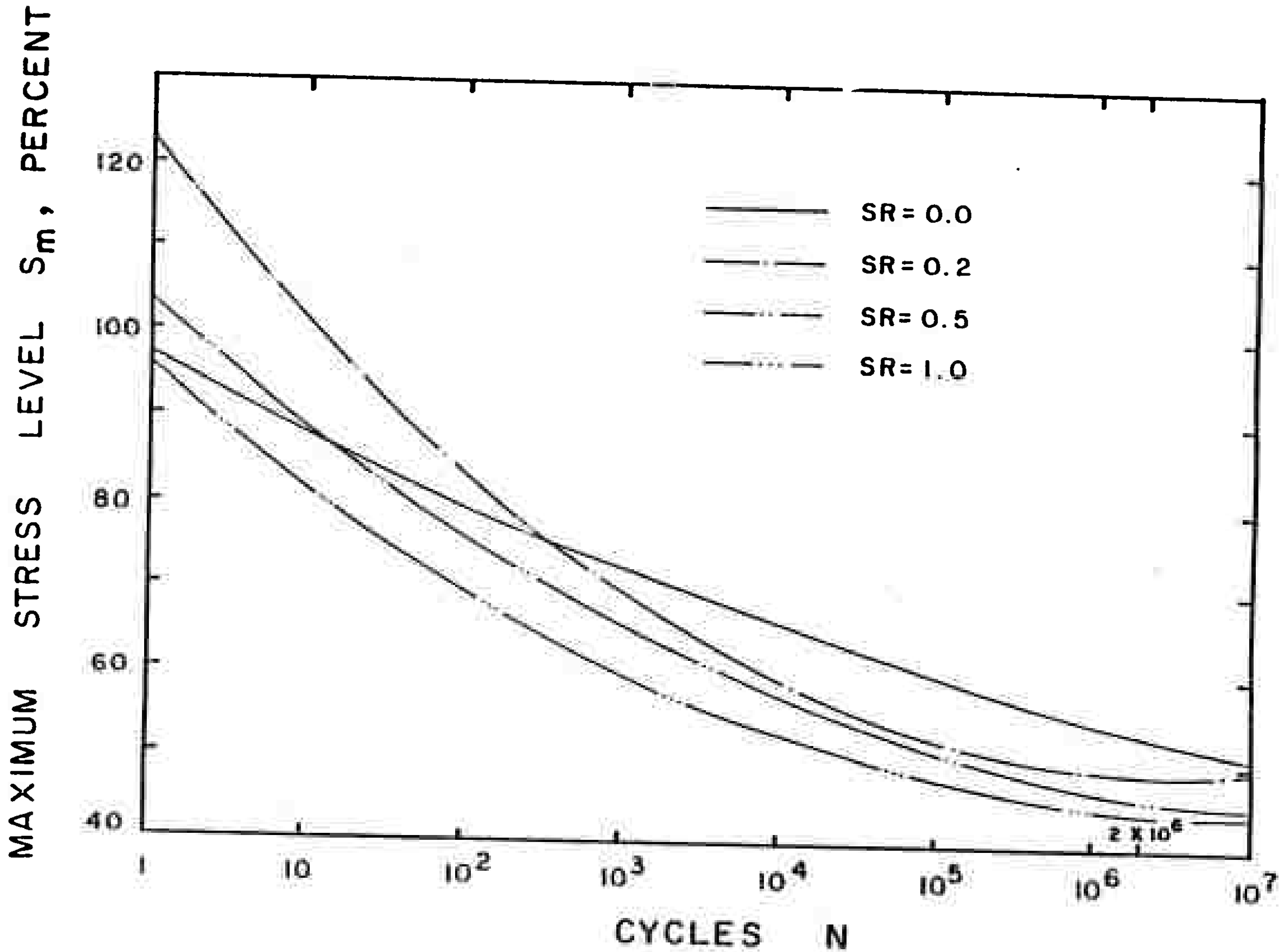

Fig. 2 Comparison of Least-Squares Polynomials for all Stress Ratios.

Publications

Several articles are in various stages of publication.

1. Refereed Journals

   a. "Cracking and Failure Mechanism of High-Strength Concrete Subjected to Biaxial State of Stress," by R. L. Carrasquillo, presented at Sixth International Conference on Cement Microscopy, held March 26 thru 29, 1984, in Albuquerque, New Mexico and published in Proceedings of Conference.

   b. "Behavior of High-Strength Concrete Under Biaxial State of Stress," by D. W. Fowler, R. L. Chen, and R. L. Carrasquillo, submitted for consideration for presentation at the American Concrete Institute Convention to be held in Chicago, Illinois, October, 1985.

2. Theses and Dissertations

   a. "Behavior of a High-Strength Concrete Model Subjected to Biaxial Compression," J. C. Herrin, December, 1982.

   b. "Analysis of a High-Strength Concrete Model Under Biaxial Compression," P. M. Castro, May, 1983.

   c. "Behavior of High-Strength Concrete in Biaxial Compression" R. L. Chen, December, 1984.

   d. "Fatigue of High-Strength Concrete Subjected to Biaxial Cyclic Compression, E. L. Nelson, to be published August, 1985.

Professional Personnel

1. John C. Herrin, Master of Science in Engineering, "Behavior of a Hign Strength Concrete Model Subjected to Biaxial Compression," December, 1982.

2. Paulo M. Castro, Master of Science in Engineering, "Analysis of a High Strength Concrete Model Under Biaxial Compression," May, 1983.

3. Robert L. Chen, Doctor of Philosophy, "Behavior of High-Strength Concrete in Biaxial Compression," 1984.

4. Erik L. Nelson, Doctor of Philosophy, "Fatigue of High-Strength Concrete Subjected to Biaxial-Cyclic Compression," to be awarded August, 1985.

5. Berjamin Briggs, "Fatigue of High-Strength Concrete Subjected to Biaxial-Cyclic Compression Tension", to be awarded August, 1986.

Interactions

1. Spoken Papers

   a. "Cracking and Failure Mechanism of High-Strength Concrete Subjected to Biaxial State of Stress," by R. L. Carrasquillo, presented at Sixth International Conference on Cement Microscopy, held March 26-29, 1984 in Albuquerque, New Mexico. Published in Proceedings of Conference.

2. Consultation Functions

   None

New Discoveries, Inventions or Patent Disclosures

None

Significant Findings

Several significant findings have resulted from the study:

1. Fatigue Behavior of High-strength concrete including the effect of a biaxial state of stress has been determined for the first time.

2. The effect of cycling below the fatigue limit has been determined as beneficial to the state strength of the material.

3. Biaxial states of stress can be detrimental to the fatigue strength of the material.